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by

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ABSTRACT

Three siltstone samples containing coal were subjected to multiple failure state tests. Originating from the Prince Mine, Nova Scotia, these behaved in a brittle fashion, due at least in part to the pressence of coal, causing violent unpredictable failures. The rock parameters were: $E = 17.9$ GPa, $\sigma_c = 63.3$ MPa (at a strain of 5.14×10^{-3}). The Hoek and Brown constants were $m = 11.5$, $s = 1$ and $m = 4.9$, $s = 0$ for broken rock (residual) respectively.

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RESULTATS D'ESSAIS TRIAXIAUX AVEC ETATS DE RUPTURE MULTIPLES SUR TROIS ECHANTILLONS DE PELITE SILTEUSE MINE PRINCE, NOUVELLE-ECOSSE

par

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RESUME

Trois échantillons de pélite silteuse contenant du charbon furent soumis à des essais triaxiaux avec états de rupture multiples. Provenant de la mine Prince de la Nouvelle-Ecosse, ceux-ci se comportèrent d'une manière fragile, due en partie à la présence du charbon, créant des ruptures imprédictibles. Les paramètres obtenus de la roche furent: E = 17.9 CPa, σ_c = 63.3 MPa (avec une déformation de 5.14×10^{-3}). Les constantes de Hoek et Brown obtenues furent m = 11.5, s = 1 et m = 4.9, s = 0 pour la roche brisée (force résiduelle) respectivement.

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INTRODUCTION

In May of 1983, three siltstone rock samples from the Prince coal mine of Nova Scotia were subjected to multiple failure state tests. The purpose of these tests was to establish the behaviour of the samples under stress and apply the results to the ground control problems of the haulage drift where the samples originated.

The multiple failure state test consists of subjecting cylindrical rock samples (length to diameter 2 - 2.5/1) to triaxial stress. The specimen is brought to successive peak strengths at various chosen confining pressures, by increasing the confinement at or just prior to reaching peak strength. After the specimen has reached the final peak and is controlled through post peak, the residual strength is obtained. The confining pressure is then slowly decreased to zero while vertical load is slowly increased; this will yield residual strength at all lesser confinements. The large quantity of data obtained in one test is sufficient to construct the limit strength curve (σ_1 vs. σ_3) and Mohr's envelope, for peak and residual strengths. The number of test samples required is thus drastically reduced in comparison to conventional triaxial tests.

ROCK TYPE

All specimens tested could be classified as grey siltstones. The rocks were composed of siltsize quartz (~90%), with opaque minerals and sand size phlogopite and obsidian forming the remaining 10% of the mineral constituents. Several thin (<.5 mm) coal bands, sometimes aligned, sometimes in a "turbulent" pattern, were present throughout the samples. Fissility was not present and parting was restricted to occur along the coal bands. Fossils were not found.

EXPERIMENTAL RESULTS

Because the samples were estimated to behave in a very brittle fashion, the uniaxial peak strength value was bypassed in testing samples 1-1 and 1-2. That this rock type fails unpredictably at low confinement was indicated during testing of sample 1-3. The multiple failure progression was

started at a 0 MPa confinement, rather than 3.45 MPa, used for the other two samples. Without indication of significant plastic deformations on the $\sigma - \epsilon$ recorders (LVDT's and strain gauges) the sample failed.

The failure mode of the specimens was highly influenced by the coal bands. Although the specimens tended to break in a planar fashion, the parting in local coal bands forced departures from this failure mode.

The stress-strain curves obtained, with confinements to 34.5 MPa, display limited plastic deformation, Fig. 1,2. Figure 3 and Table 2 present the measured failure angles and theoretical calculations (based on Coates' (1) functional relations, below) used to obtain the Mohr peak strength envelope.

Coates' functional relations between stresses:

$$\frac{\sigma_1 + \sigma_c}{\sigma_3 + \sigma_c} = \tan^2 (45 + \phi/2) = f$$

$$\sigma_1 = \sigma_3 f + \sigma_c f - \sigma_c$$

$$\sigma_1 = \sigma_3 f + \sigma_c (f-1)$$

when $\sigma_3 = 0$

$$\sigma_1 = \sigma_c (f-1) = Qu$$

$$\therefore \quad \sigma_1 = \sigma_3 f + Qu$$

$$\text{or} \qquad \sigma_1 = \sigma_3 [\tan^2(45 + \phi/2)] + Qu$$

where

σ_c = intrinsic stress resulting from intermolecular attraction
Qu = uniaxial compressive strength
ϕ = internal angle of friction

The Mohr peak and residual strength envelopes are presented in Fig. 3. The peak and residual strength curves, σ_1 *vs.* σ_3, are presented in Fig. 4.

Although sample 1-1's results are presented in Table 1, its reduced size (L/D = 1.66) and partial results (due to a malfunction of the sensitivity adjustment of the LVDT-axial load recorder, the strains were not registered properly) precluded its inclusion with the other two standard size samples, for processing.

DISCUSSION

The Warwersick (2) and Hoek and Brown (3) criteria can be used to evaluate the mechanical properties of this rock.

The samples' behaviour during testing permits classification according to Warwersick's Class I (more ductile) or Class II (brittle) system. A brittle rock under uniaxial compression will have linear response in the elastic $\sigma - \varepsilon$ range; fracturing will accelerate rapidly around peak strength, continuing self sustained through post failure. Little strength remains after peak strength is reached and fracture can be arrested only if strain energy is extracted from the specimen (positively sloped post peak $\sigma - \varepsilon$ trace). Although the uniaxial post-peak was not reached in these tests, the rapid and unpredictable failure of the specimen, absence of plastic deformation, and linear $\sigma - \varepsilon$ plot in the elastic range indicate that these specimens behave in a brittle or Class II fashion under uniaxial compression. The post-peak behaviour at 27.6 MPa confinement is Class I, i.e., need to impart energy to the specimen to continue fracturing. It is probable that the discontinuities created by the coal bands are at least in part responsible for the brittle behaviour of these specimens tested under low confinement. Because these discontinuities would open readily in the plastic region, little strength would be left (since the coal is omnipresent) to prevent these cracks from connecting and causing the failure of the specimen.

The regression calculations to obtain Hoek and Brown's "m" and "s" constants, Appendix 1,2, based on their empirical relationship,

$$\sigma_1 = \sigma_3 + \sqrt{m\,\sigma_c\sigma_3 + s\sigma_c^2}$$

where σ_1 is the major principal stress at failure

σ_3 is the minor principal stress applied to the specimen

σ_c is the uniaxial compressive strength of intact rock

m,s are constants which depend upon the properties of the rock and upon the extent to which it has been broken before being subjected to the stresses σ_1 and σ_3

yield values of m = 11.5, s = 1, for intact rock and m = 4.9, s = 0 for broken rock (based on residual strength). The decrease in m from intact to broken rock is expected because m is directly related to deviator stress. This is in agreement with the Hoek and Brown trend. The value of s for broken rock is lower than unity (intact rock) as it should be; the zero value indicates very little strength remains. According to Hoek and Brown, s reflects the tensile component of the rock matrix strength decreasing to zero as the rock matrix is broken up by the formation of fractures; residual strength reflects the friction between particles after major fracturing has occurred.

CONCLUSIONS

The rock specimens tested, siltstone from the Prince Mine, Nova Scotia, behaved in a brittle fashion, due at least in part to the coal bands present in the samples. Violent unpredictable failure of the uniaxially compressed sample precluded obtaining post peak behaviour. The rock parameters are: modulus of elasticity of 17.9 GPa, unconfined compressive strength of 63.3 MPa, with associated strain of 5.14×10^{-3}. The behaviour under uniaxial compression was Type II (brittle), at 27.6 MPa confinement, Type I (more ductile). The Hoek and Brown constants are m = 11.5, s = 1 and m = 4.9, s = 0 for intact and broken rock (residual) respectively. All of this data is based on samples with length to diameter ratios of about 1.95.

REFERENCES

(1) Coates, D.F. "Rock mechanics principles"; Monograph 874; Energy, Mines and Resources, Canada; 1981.

(2) Wawersick, W.R. and Brace, W.F. "Post failure behaviour of an arenite and diabase"; Rock Mechanics, 3, p 81-85; 1971.

(3) Hoek, E. and Brown, E.T. "Underground excavations in rock"; Institution of Mining and Metallurgy, 527 pp; 1980.

Table 1 - Multiple failure state test results

Sample/σ_3	0 MPa						3.45 MPa			6.90 MPa			10.34 MPa			13.79 MPa		
	σ_{1peak} (MPa)	ϵ_{peak} x 10^{-3}	E (GPa)	ν	σ_r	L/D	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)
1-1	-	-	-	-	-	1.66	62.5	-	-	75.2	-	-	84.4	-	-	94.5	-	-
1-2	-	-	-	-	-	1.94	85.1	6.4	32.8	100.0	7.9	47.6	112.9	8.9	60.1	125.3	9.9	72.0
1-3	63.3	5.4	17.9†/15.3*	0.18	-	1.95	-	-	-	-	-	-	-	-	-	-	-	-

- not available

† using strain gauges

* using LVDT's

Sample/σ_3	17.24 MPa			20.68 MPa			24.13 MPa			27.57 MPa			31.02 MPa			34.47 MPa		
	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (GPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)	σ_{1p} (MPa)	ϵ_p x 10^{-3}	σ_r (MPa)
1-1	101.8	-	-	109.9	-	-	118.0	-	-	127.7	-	-	135.9	-	-	145.1	-	-
1-2	137.5	11.3	82.8	147.5	12.1	93.9	154.3	13.3	106.6	160.2	13.7	115.0	-	-	-	-	-	-
1-3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 2 - Comparison of failure properties obtained from the multiple failure state tests

σ_3	α_m (degrees)	α_{th} (degrees)	ϕ_m (degrees)	ϕ_{th} (degrees)	C_m (MPa)	C_{th} (MPa)
			Sample 1-2			
3.45		68.3		46.6		13.0
6.90		66.5		43.0		15.3
10.34		65.5		41.0		15.9
13.79		64.8		39.6		16.6
17.24		64.3		38.6		17.3
20.68		63.6		37.2		18.0
24.13		62.8		35.6		18.8
27.57	60	61.9	30.0	33.8	23.0	20.0
			Sample 1-3			
0	61.8		33.6		16.8	
			ϕ_r (degrees)		Cr (MPa)	
			Sample 1-2			
Taken approximate envelope, in the range of σ_3 = 13.79-24.13 M MPa			38		7.3	

m = measured ; th = theoretical; r = residual

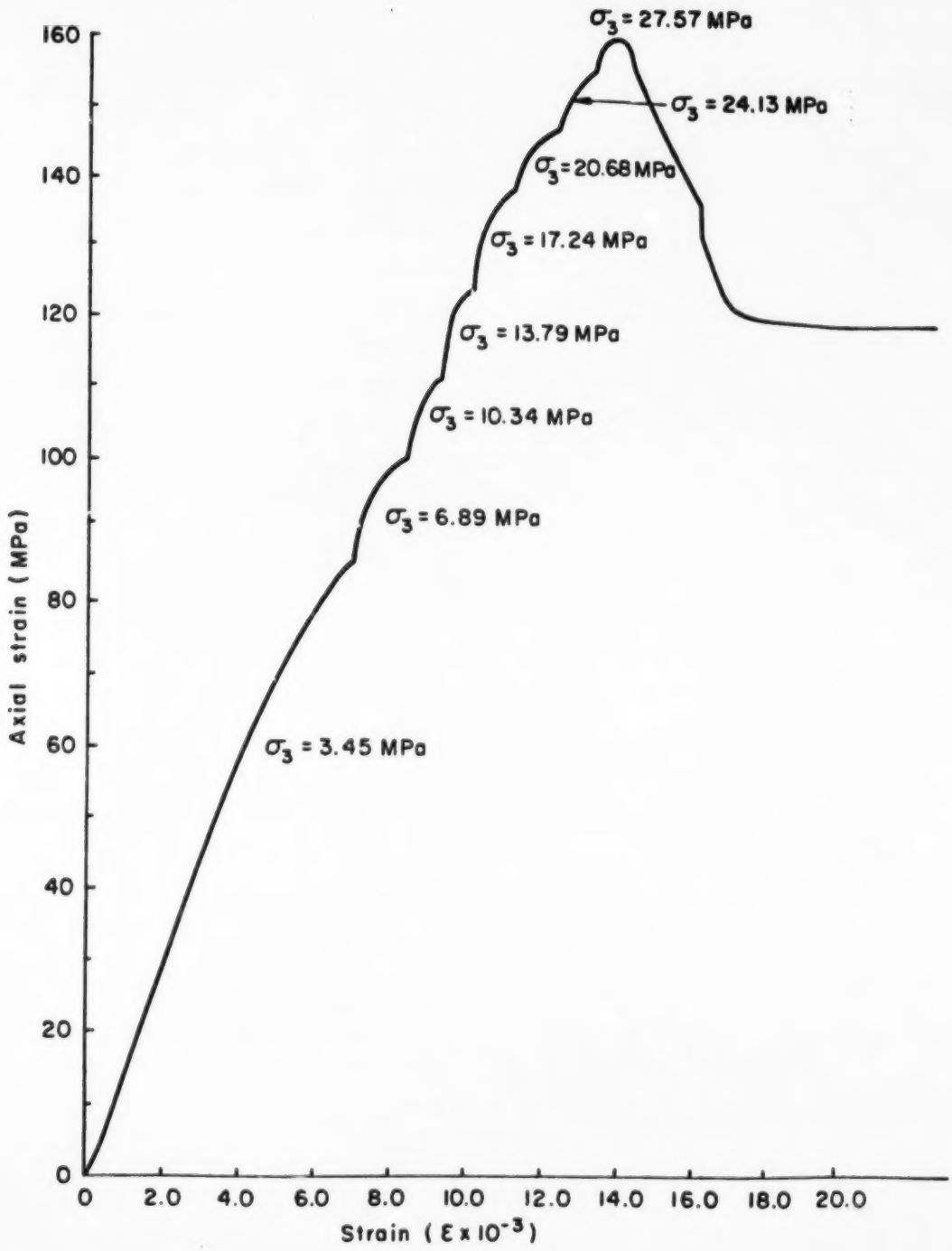

Fig. 1 - Stress-strain plot of sample 1-2

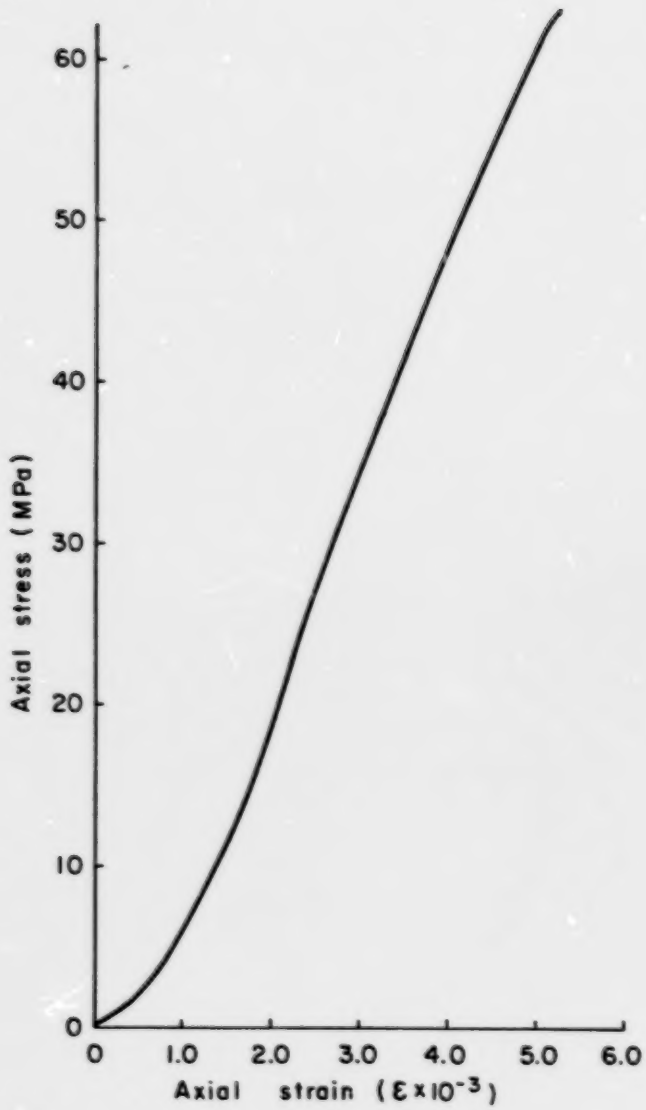

Fig. 2 - Stress-strain plot of sample 1-3

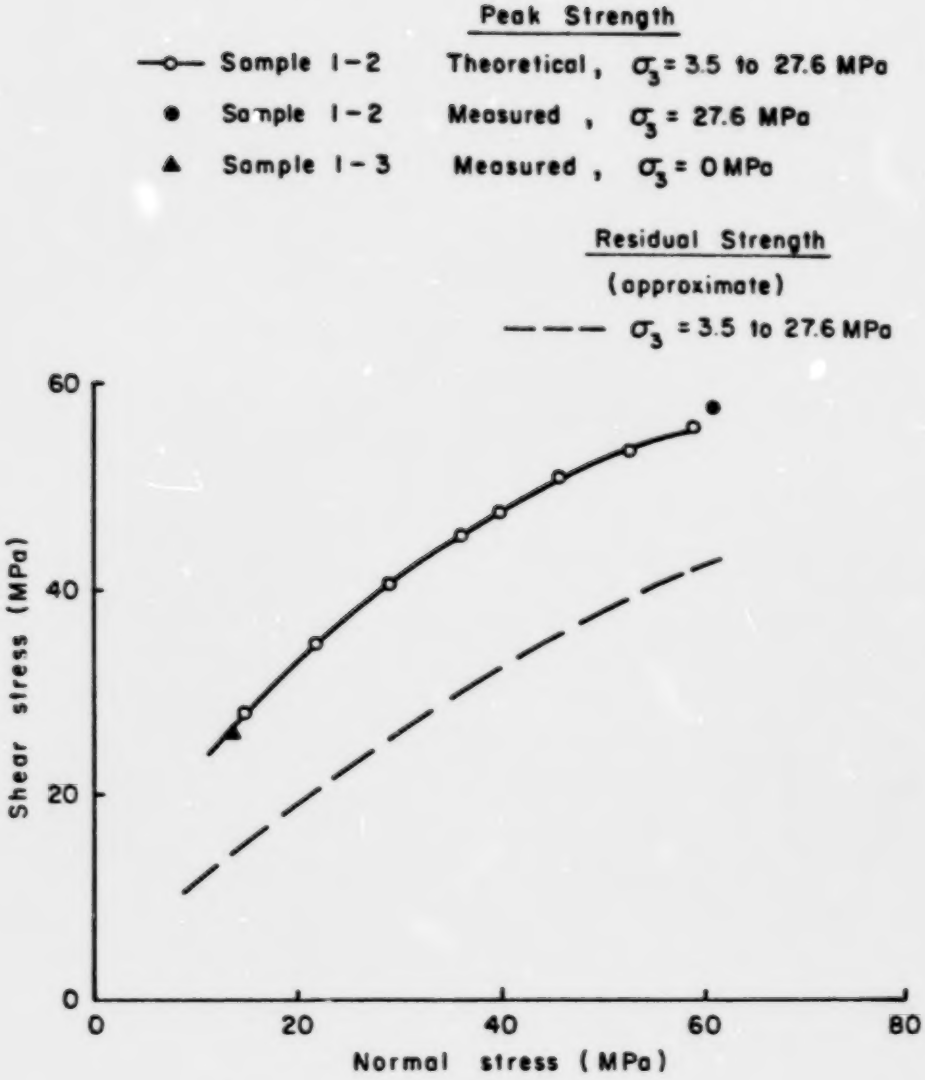

Fig. 3 - Mohr enveloppes for peak and residual strength, Prince Mine siltstone

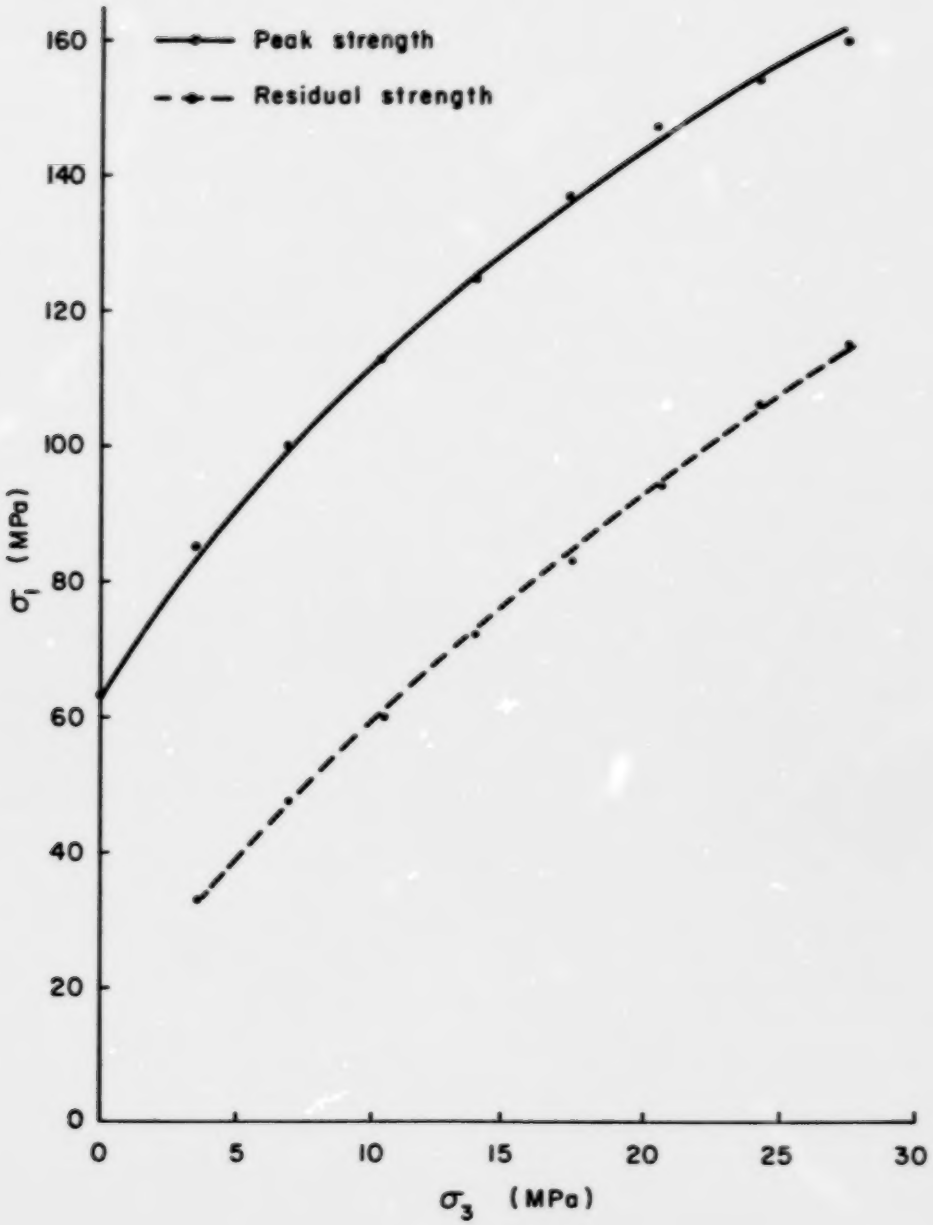

Fig. 4 - Peak and residual strength curves, Prince Mine siltstone

APPENDIX 1

CALCULATION OF HOEK AND BROWN'S CONSTANTS

$$\sigma_1 = \sigma_3 + \sqrt{m\,\sigma_c\,\sigma_3 + s\,\sigma_c^2}$$

FOR INTACT ROCK

	x_i	y_i	$x_i y_i$	x_i^2	y_i^2
	0	4006	0	0	16055167
	3.5	6667	23334	12	44448889
	6.9	8668	59809	48	75134224
	10.3	10527	108428	106	110817729
	13.8	12432	171561	140	154554674
	17.2	14462	248746	296	209149444
	20.7	16078	332185	428	258502084
	24.1	16952	408543	581	287370304
	27.6	17583	485291	762	309161889
Σ	124.1	107376	1838528	2423	1465194404
Σ^2	15401	11529605376			

$y = (\sigma_1 - \sigma_3)^2 \quad x = \sigma_3 \quad n = 11 \quad s = 1$ for intact rock

$$\sigma_c^2 = \frac{\Sigma y_i}{n} - \left[\frac{\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}}{\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}}\right]\frac{\Sigma x_i}{n}$$

$$m = \frac{1}{\sigma_c}\left[\frac{\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}}{\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}}\right]$$

$$r^2 = \frac{\left[\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}\right]^2}{\left[\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}\right]\left[\Sigma y_i^2 - \frac{(\Sigma y_i)^2}{n}\right]}$$

$\sigma_c = 62.9$ MPa

$m = 11.5$

$r^2 = 0.93$

APPENDIX 2

CALCULATION OF HOEK AND BROWN CONSTANTS

$$\sigma_1 = \sigma_3 + \sqrt{m\,\sigma_c\,\sigma_3 + s\,\sigma_c^2}$$

FOR BROKEN ROCK

	x_i	y_i	$x_i y_i$	x_i^2	y_i^2
	3.5	861	3015	12	742049
	6.9	1656	11429	48	2743959
	10.3	2480	25544	106	6150598
	13.8	3387	46744	190	11473395
	17.2	4298	73928	296	18473781
	20.7	5358	110916	428	28710736
	24.1	6806	164031	581	46325039
	27.6	7638	210830	762	58350654
Σ	124.1	32484	646437	2423	172970211
Σ^2	15401	1055210256			

$y = (\sigma_R - \sigma_3)^2 \quad x = \sigma_3 \quad n = 10$

σ_c to be used = intact rock = 53.3 MPa

$$m = \frac{1}{\sigma_c}\left[\frac{\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}}{\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}}\right]$$

when s gives o or negative values:

$$m = \frac{\Sigma y_i}{\sigma_c \Sigma x_i}$$

$$s = \frac{1}{\sigma_c^2}\left[\frac{\Sigma y_i}{n} - m\,\sigma_c\,\frac{\Sigma x_i}{n}\right]$$

$$r^2 = \frac{\left[\Sigma x_i y_i - \frac{\Sigma x_i \Sigma y_i}{n}\right]^2}{\left[\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}\right]\left[\Sigma y_i^2 - \frac{(\Sigma y_i)^2}{n}\right]}$$

$m = 4.9$

$s = 0$

$r^2 = 0.99$